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Akademisk avhandling som för avläggande av filosofie doktors-
examen vid matematisk-naturvetenskapliga fakulteten vid uni-
versitetet i Lund kommer att offentligens försvaras å Fysiska
institutionens föreläsningssal B fredagen den 21 mars 1975
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Nuclear reactions induced by nuclei at high energy have been studied in nuclear emulsions for more than two decades. Until recently high energy nuclei were only available in the cosmic radiation. In 1971 the Berkeley Bevatron was used for acceleration of nuclei with charge $Z \leq 10$ to energies up to 2.1 GeV/nucleon. Since this successful start even heavier nuclei have been accelerated to this energy.

Characteristics of nucleus-nucleus interactions have been studied by means of different types of detectors. A common detector is nuclear emulsion which has the important advantage that all charged particles leaving the interaction point can be detected. Consequently the emission of a certain kind of charged particles can be studied as a function of emission properties of other particles or as a function of the degree of disintegration of the interacting nuclei.

The wavelength associated with a 100 MeV nucleon is about the same as the average spacing of nucleons in a nucleus. In the tens of MeV-region, however, the de Broglie wavelength is comparable with the size of the whole nucleus. For an incident nucleon in the first case the target nucleus appears as a cloud of nearly independent nucleons. In the second case the target appears as an opaque body which absorbs the incident particle. A compound nucleus is therefore often formed at low energy. By the capture of the incident particle the nucleus is transformed to an excited state. In the second stage of the reaction the nucleus is cooled by particle emission and emission of electromagnetic radiation. The deexcitation products are emitted iso-

tropically in the rest system of the nucleus.

At high energies an incident nucleon is likely to interact individually with the target nucleons. The nucleons participating in collisions often have energy enough to leave the nucleus. On their way out new interactions with the nuclear constituents can occur. In this way a cascade may be generated. Since the incident particle has a large momentum component in the forward direction the particle emission is anisotropic in the rest system of the target nucleus.

The target nucleus may be totally disintegrated during the cascade stage but it is more likely that a residual nucleus is formed. The residual nucleus may have very large excitation energy and angular momentum and decays in a way analogous to that of a compound nucleus.

In a first approximation nucleus-nucleus interactions have been treated as a superposition of independent nucleon-nucleus collisions. Recent investigations have however pointed to large differences from this simple view, especially for interactions with a complete break-up of the interacting nuclei. Non-statistical models seem to give a more adequate description of these collisions.

Some physicists have tried to simulate interactions between nuclei by Monte-Carlo calculations using the Fermi gas model for the nucleus. For energies below the pion threshold agreement between the calculations and experimental results is often found. Also in the GeV region the energy and angular distributions of protons are still in agreement with the calculations. However, in this energy region the calculations cannot satisfactorily account for the emission of multiply charged fragments

($Z \geq 2$). The cross section for emission of multiply charged particles increases rapidly when the incident energy is increased from a few hundred MeV/nucleon to a few GeV/nucleon. This phenomenon is difficult to explain by existing models. The energy distribution of the fragments in the rest system of the emitting nucleus, has a low energy part which may be explained by a large reduction of the Coulomb barrier. There is also a high energy tail in the energy spectrum of fragments which cannot possibly be explained by any evaporation mechanism.

The present dissertation is based on investigations published in the following papers:

- I. Nuclear Disintegrations Produced by Multiply Charged Particles.
Physica Scripta 5, 5 (1972)
(in collaboration with I. Otterlund and R. Resman).
- II. Emission of Helium Nuclei in Heavy Ion Interactions at Energies ≥ 100 MeV/nucleon.
Z. Physik 259, 245 (1973)
(in collaboration with I. Otterlund).
- III. Fast Helium Nuclei in Interactions Induced by Very Heavy Nuclei.
Z. Physik 268, 1 (1974)
(in collaboration with B. Jakobsson and I. Otterlund).
- IV. Pion and Proton Emission in Interactions Induced by Relativistic Heavy Nuclei with $Z \geq 12$.
Accepted for publication in Z. Physik.
(in collaboration with B. Jakobsson and I. Otterlund).

Preliminary reports are given at:

1. The Conference of the Swedish National Committee for Physics, Lund 1972.
2. The Fifth International Conference on High Energy Physics and Nuclear Structure, Uppsala 1973.

In the experiments described in these papers nuclear emulsion is used as detector. Papers I and II are based on 101 nucleus-nucleus interactions studied in Ilford K2 emulsions. The charge of the projectile nucleus was ≥ 3 and the energy ≥ 100 MeV/nucleon. K2 emulsions have a very low sensitivity. In the emulsion stack used only particles with an energy loss larger than that of a 10 MeV proton were registered as tracks. Consequently, not all charged particles emitted in an interaction are detected. However, it is a great advantage that charge separation between even very short tracks of protons and helium nuclei is obtained with good accuracy. In papers III and IV 82 interactions are studied with the charge of the projectile nucleus ≥ 12 and with the energy > 1 GeV/nucleon. The interactions are registered in Ilford G5 emulsion, which is electron sensitive and consequently all charged particles are registered as tracks.

In paper I energy and angular distributions of protons with $E_p < 10$ MeV and helium nuclei with $E_{He} < 200$ MeV are analysed. The low energy protons and helium nuclei ($E < 30$ MeV) are emitted almost isotropically in the rest system of the excited target nucleus. However, part of the low energy protons can only be accounted for by assuming extremely low values of the Coulomb barrier. The helium nuclei are partly emitted from excited fragments and partly as a result of direct interactions. The idea of direct interactions is supported by the large momentum trans-

fer to a large amount of target helium nuclei. For energies < 30 MeV approximately twice as many protons as helium nuclei are emitted. It is also found that the heavy target fragments are preferentially emitted in the forward direction.

The helium emission is further analysed in paper II. It is found that fast helium nuclei are preferentially emitted in large stars. In the energy interval 40-200 MeV the differential energy spectrum of the target helium nuclei can be represented by a power law:

$$N(E) dE = \text{const} \cdot E^{-\alpha} dE \quad (1)$$

It is evident that quasielastic nucleon-helium scattering cannot account for all fast helium nuclei. This statement is supported by the fact that helium nuclei are emitted in the backward hemisphere with energies larger than expected from intranuclear $p - {}^4\text{He}$ scattering.

The emission of helium nuclei in interactions induced by heavy nuclei ($Z \geq 12$) with energies > 1 GeV/nucleon is investigated in paper III. The constant α in formula 1 is found to be 1.8 ± 0.1 . This can be compared with α -values of about 3.3 in proton and pion induced interactions and $\alpha \approx 7$ in $p - {}^4\text{He}$ elastic scattering. The angular distribution of fast target helium nuclei is only slightly anisotropic in the laboratory system. Therefore some production mechanism in addition to quasielastic nucleon-helium scattering is probably needed to account for the angular and energy distributions of fast helium nuclei. In some interactions the number of fast helium nuclei is anomalously large in comparison with predictions from existing models. Furthermore the frequency of helium nuclei and heavier fragments depends on the size and on the degree of disintegration of the interacting nuclei.

In paper IV the emission of singly charged particles is analysed. For emission angles larger than 30° the angular and energy distributions of target protons are similar in proton-nucleus and nucleus-nucleus interactions. However, in nucleus-nucleus interactions a forward peak of high energy target protons ($E_p \geq 200$ MeV) is observed. In contradiction to proton-nucleus interactions the $\log \tan \theta$ distributions of pions in nucleus-nucleus interactions have small standard deviations even in interactions with a large target disintegration. In interactions with almost complete break-up of the interacting nuclei and large pion production large transverse momenta are transferred to projectile protons. In the latter type of nucleus-nucleus interactions there is an excess of pions in comparison to the expected multiplicity for independent nucleon-nucleon interactions.

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